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Collaboratory for the Study of Earthquake Predictability: Research and Development to Support USGS Operational Earthquake Forecasting

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Abstract

The Collaboratory for the Study of Earthquake Predictability (CSEP) is an international partnership to develop and maintain a cyberinfrastructure for the rigorous prospective evaluation of earthquake forecasting models. This project supported the CSEP operations at the Southern California Earthquake Center (SCEC) from 1 July 2014 – 31 December 2014. During this period, up to 434 forecasts were being evaluated by CSEP worldwide. The main testing regions are California (86 models), Japan (229 models), New Zealand (58 models), and Italy (48 models). In addition, 13 global models and 1 oceanic transform fault model were also under test at the SCEC/CSEP Testing Center. Efforts to register external forecasts were focused on the M8 forecasts, submitted by V. Kossobokov, and forecasts to be submitted by T. Bleier and the Quakefinder group. A main focus for CSEP testing during 2014 was the Canterbury Retrospective Experiment, which used the dense dataset collected during the 2010-2013 Canterbury sequence. The results 2 show, for the first time, that the short-term performance of the physics-based models, which update forecasts with Coulomb stress changes computed from the observed faulting, can significantly outperform models updated only with the conventional seismicity statistics (Werner et al., 2015a,b).

Introduction

Through its CSEP testing center, SCEC supports the development of short-term earthquake forecasting by researchers in the SCEC community and the U. S. Geological Survey (USGS). CSEP is a cyberinfrastructure for the empirical validation of forecasting methods that is rigorous and reproducible, adhering to consistent data standards and strict blind testing procedures, and it is capable of sustaining long-term comparative experiments over large geographic areas.

While this project is focused on the basic research problems of earthquake system science, it contributes to USGS plans for the deployment of operational earthquake forecasting (OEF) (USGS, 2014). Forecasting models considered for operational purposes must demonstrate reliability and skill with respect to established reference forecasts, such as the long-term, time-independent models used in probabilistic seismic hazard analysis (ICEF, 2011; Jordan et al., 2014; Marzocchi et al., 2015; Field et al., 2015). Validation of reliability and skill requires objective evaluation of how well forecasting models correspond to data collected after the forecast has been made (prospective testing), as well as checks against data previously recorded (retrospective testing).

CSEP Activities and Accomplishments

We briefly summarize CSEP activities and accomplishments during the performance period of 1 July 2014 – 31 December 2014.

1. Prospective testing of earthquake forecasts. The main purpose of CSEP is to provide an infrastructure for the automated prospective testing of earthquake forecasts in a variety of seismically active regions to assess the reliability and skill of forecasting methods (Zechar et al., 2010). CSEP now accepts two types of forecasts for prospective evaluation:

    a. Forecasts from codes managed within the CSEP operational environment.

        - As of 1 April 2015, 434 CSEP-managed forecasts were under evaluation worldwide (Figure 1). The main testing regions are California (86 models), Japan (229 models), New Zealand (58 models), and Italy (48 models). In addition, 13 global models and 1 oceanic transform fault model are also being tested at the SCEC/CSEP Testing Center.

    b. External forecasts registered into CSEP with appropriate metadata and evaluated by CSEP testing methods.

        - Efforts to register external forecasts were focused on the M8 forecasts, submitted by V. Kossobokov, and forecasts to be submitted by T. Bleier and the Quakefinder group.
        - PDE authorized data source and M8FOG (M8 Fixed Odds Gambling) evaluation test, which is a prototype test for M8 evaluation, was introduced to the SCEC/CSEP testing center with Version 13.10.0 (October 21, 2013) software release. However, PDE authorized data source changed catalog data format and discontinued distribution of their historic data through ftp://hazards.cr.usgs.gov site as of spring 2014. CSEP testing center had to postpone evaluation of all new M8 forecasts, as submitted by Volodya Kossobokov to the center, until PDE catalog becomes available through the ANSS Comprehensive Catalog (ComCat) collection.
        - The CSEP group worked with QuakeFinder developers to agree on XML schema to define format for external forecasts to be provided by QuakeFinder group to the CSEP for evaluation. The latest XML schema definition and example of external forecast (available at https://northridge.usc.edu/trac/csep/wiki/CircleForecastXMLSchema) has been provided to the QuakeFinder group, and CSEP group is awaiting for an example of external forecast as it would be provided to the CSEP for evaluation. Evaluation techniques, to be applied to QuakeFinder external forecasts, are still under consideration.

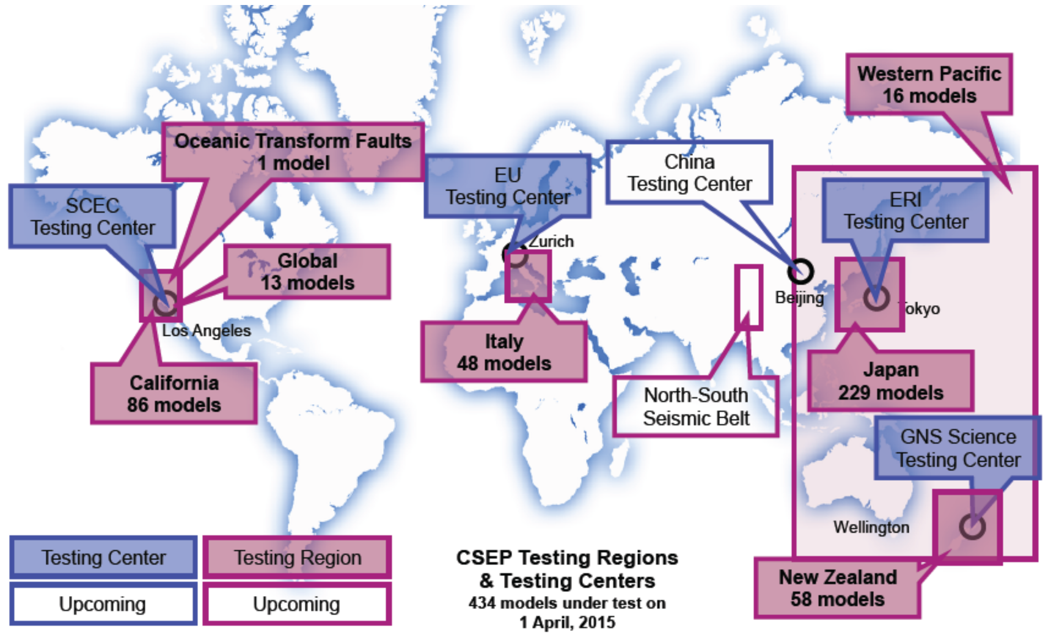


Figure 1. CSEP testing regions and testing centers, showing the number of forecasts being prospectively tested in each as of 1 April 2015.

2. Calibration and retrospective testing of earthquake forecasts. The standardization of testing procedures and data sets by CSEP provides an ideal environment for the calibration and retrospective testing of earthquake forecasts. Retrospective testing is usually necessary to prepare forecasts for prospective testing.

    a. A main focus for CSEP testing during 2014 was the Canterbury Retrospective Experiment, which used the dense dataset collected during the 2010-2012 Canterbury sequence. The energetic Canterbury sequence was initiated by the M7.1 Darfield earthquake on 4 Sept 2010. The Darfield mainshock caused relatively light damage, but a M6.3 aftershock directly beneath Christchurch on 22 Feb 2011 destroyed the city center, killing 185 people. Subsequent aftershocks compounded the damage and undermined recovery efforts.

    b. The scientific goals were to (i) improve our understanding of the physical mechanisms governing earthquake interaction and triggering using the data collected from the Canterbury sequence; (ii) improve short-term earthquake forecasting models and time-dependent hazard assessment for the Canterbury region and to apply lessons learned elsewhere; and (iii) understand the influence of poor-quality, real-time data on the skill of forecasts that might be issued in real time in an operational setting. Eight different research groups from the US, New Zealand, Japan and Europe contributed more than 20 physics-based and statistical forecasting models (1-day, 1-month, 1-year) to this experiment.

    c. CSEP testing framework was updated with Version 15.4.0 software release (April 2, 2015) to invoke statistical T and W evaluation tests across multiple forecasts groups in the Canterbury experiment. This functionality can also be applied to other testing regions.

    d. In the Canterbury experiment, forecast start times are reset before major events. New functionality to support forecast start time reset in the generation and evaluation of Canterbury forecasts was added to the CSEP Version 14.10.0 (October 14, 2014) software release.

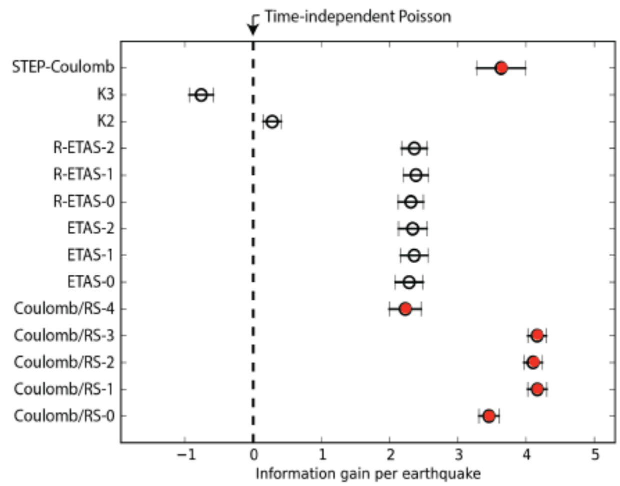
    e. All 1-day, 1-month and 1-year forecasts, using realtime and best available GeoNet catalogs, have been generated during August, 2014 – March 2015 time period.

f. All forecasts groups for both test cases (using reatime and best available catalogs) have been evaluated with N, CL, M, S, T and W evaluation tests as of April 1, 2015.

g. Canterbury provided an excellent dataset for evaluating forecasting performance during an intense, multi-fault earthquake sequence. The results in Figure 2 show, for the first time, that the short-term performance of the physics-based models, which update forecasts with Coulomb stress changes computed from the observed faulting, can significantly outperform models updated only with the conventional seismicity statistics (Werner et al., 2015a,b).

h. All models from the Canterbury Retrospective Experiment will continue to be managed by CSEP, allowing them to be prospectively tested against future data from the region.

Figure 2. Preliminary results from the retrospective Canterbury experiment recently conducted in CSEP. The circles with error bars show the average information gain (natural log of the probability gain) per earthquake relative to a time-independent reference model (dashed line). The 14 forecasts in this experiment are listed on the left axis. 394 earthquakes with M > 3.95 were observed during the 18-month forecasting interval. This experiment is the first CSEP demonstration that physics-based models (red dots) can outperform statistical models (open circles) in short-term forecasting.



3. Development of ensemble forecasting models. Ensemble averaging techniques allow different types of forecasting models to be combined to obtain forecasts that often have higher reliability and skill than any of the individual components. CSEP provides an environment for the development of ensemble forecasts.

   a. Marzocchi et al. (2012) have applied variants of Bayesian model averaging to the RELM models to demonstrated modest probability gains. Higher probability gains have been obtained for the RELM model ensemble by Rhoades et al. (2014) using the new technique of multiplicative model averaging.

   b. Matteo Taroni (INGV) was provided with complete set of Canterbury 1-day and 1-month forecasts generated using realtime and best available GeoNet catalogs. Matteo is using these forecasts to ensemble Bayesian models for the Canterbury experiment.

4. Interactions with NEIC on earthquake cataloging. The USGS National Earthquake Information Center is developing ComCat, a new system for accessing seismicity catalog and parametric earthquake information. CSEP is assisting NEIC in developing this database with a structure suitable for OEF.

   a. Motivated by CSEP needs, ComCat will include an interface that allows a user to obtain a version of the catalog as it appeared at a particular time. This will be done by saving all versions of event information and building custom catalogs in response to requests rather than by saving snapshots of the catalog at given intervals. The chosen approach provides CSEP with the flexibility required to properly test short-term forecasts.

   b. A 31-day delay, that has been applied to all raw catalog retrievals within CSEP, was removed as of CSEP Version 14.10.0 (October 14, 2014). This change to the raw catalog retrieval and archival procedures provides daily archive of all downloaded raw catalogs (ANSS, CMT) by the

CSEP testing center at SCEC. Such daily catalog archive might be useful for future retrospective experiments where effect of using realtime data is considered (such as OEF).

5. Testing of GEM models. The Global Earthquake Model (GEM) project is developing the first homogeneous hazard and risk model for the entire world (Bird et al., 2015). The GEM is being assembled from data, known physical properties, statistical descriptions of physical phenomena, and expert opinion.
   a. The GEM Testing Center at GFZ Potsdam, led by Danijel Schorlemmer, has collaborated with CSEP in the software development and testing programs. For seismicity rate model testing, Potsdam uses testing capabilities developed at the SCEC CSEP testing center and has created new testing experiments that combine GEM models with other CSEP-registered models (e.g. RELM models). The joint tasks include the analysis of the test results for the 3-month model experiment in California and comparative tests with UCERF2.
   b. Peter Bird (UCLA) submitted updated version of SHIFT_GSRM global model that provides higher-resolution 0.1-degree magnitude bins to the CSEP testing center. That model was installed and tested within CSEP testing center as of Version 14.1.0 release. To store and to evaluate large forecast file for high-resolution global experiment, CSEP added new functionality to allow for HDF5 binary data format of such forecasts.
   c. To support large number of files for reduced testing latency of 30-minute within CSEP testing center at SCEC, CSEP Version 14.4.0 (April 29, 2014) added new functionality of applying GZIP compression to store forecasts files within CSEP testing center.
6. Testing of ground motion predictions. Because the CSEP software distribution implements the complete work-flow for unbiased and prospective tests, it is the best basis for extensions covering tests of other phenomena, including ground motion predictions, both empirical (e.g., NGA GMPEs) and simulation-based (e.g., CyberShake).
   a. The Potsdam group has developed procedures for testing intensity prediction equations (IPEs) based on the CSEP testing center software, and a similar development is underway for ground-motion prediction equations (GMPEs). Potsdam is also developing procedures for testing complete earthquake hazard and risk models. The first target is the testing of the 1996 national seismic hazard map against 17 years of ground motion observations.
7. Testing of geodetic anomaly detectors. Detection of transient geodetic anomalies is an important research area for earthquake forecasting. CSEP provides the infrastructure for running and evaluating automated anomaly detection algorithms.
   a. Results from the SCEC transient detection effort were published in a special section of *Seismol. Res. Lett.* (Lohman and Murray, 2013), including submissions related to the generation of synthetic data and development of algorithms that use geodetic observations to detect transient deformation signals.
   b. Three completely different testing approaches are now running automatically at the CSEP online testing center, one with several versions.
   c. Bill Holt, Stony Brook University, contacted Masha Liukis and John Yu in August 2014 to provide him with assistance to install his transient detection model within testing center. Login account on CSEP development server was created for Bill’s group, and they were working on compiling their codes and setting up a test case required by the model installation on the CSEP server.

Publications

Research activities contained in the following publications were supported by this contract:

Field, E. H., and T. H. Jordan (2015), Time-dependent renewal-model probabilities when date of last earthquake is unknown, *Bull. Seismol. Soc. Am.*, **105**, doi:10.1785/0120140096.

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